Pulsed Lidar for Measurement of CO2 Concentrations for the ASCENDS Mission - Update

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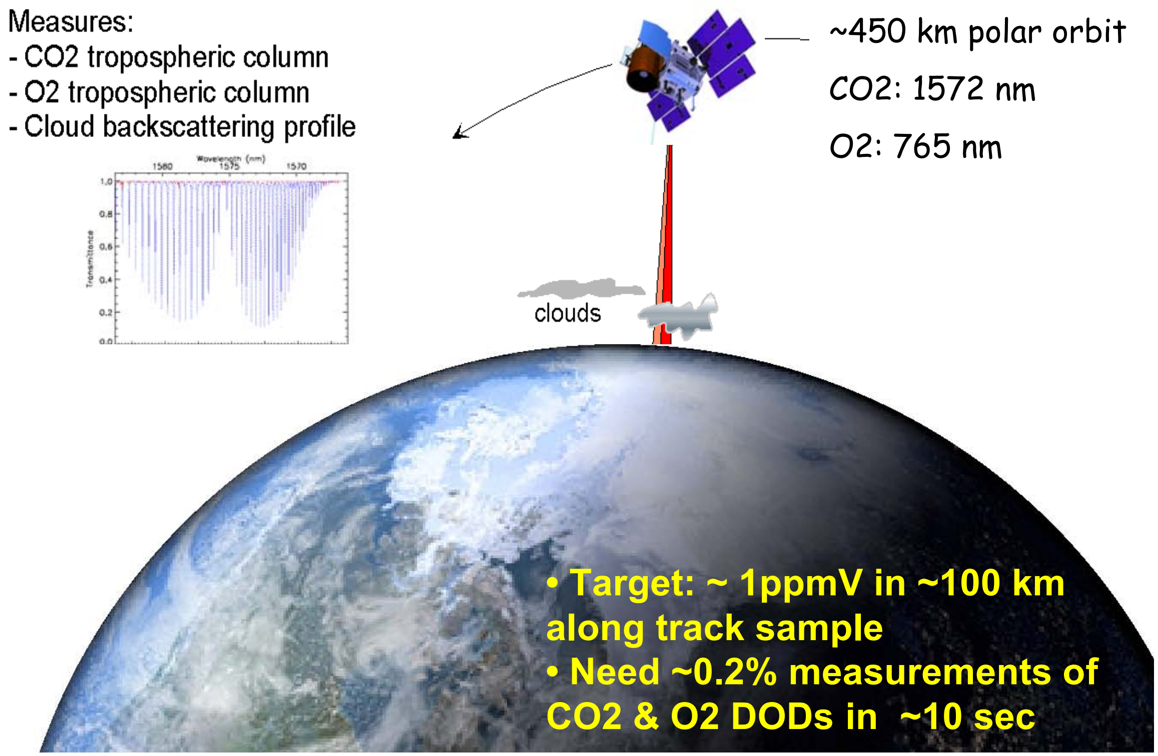
Laser Sounder Approach
A candidate for the ASCENDS Mission

Simultaneous laser measurements:

1. CO_2 lower tropospheric column
   One line near 1572 nm
2. O_2 total column (surface pressure)
   Measure 2 lines near 765 nm
3. Altimetry & atm backscatter profile
   Range resolved CO_2 signal



Measurements use:

- Pulsed lasers
- ~10 KHZ pulse rates
- 8 laser wavelengths for CO_2 line
- Time resolved photon sensitive receiver

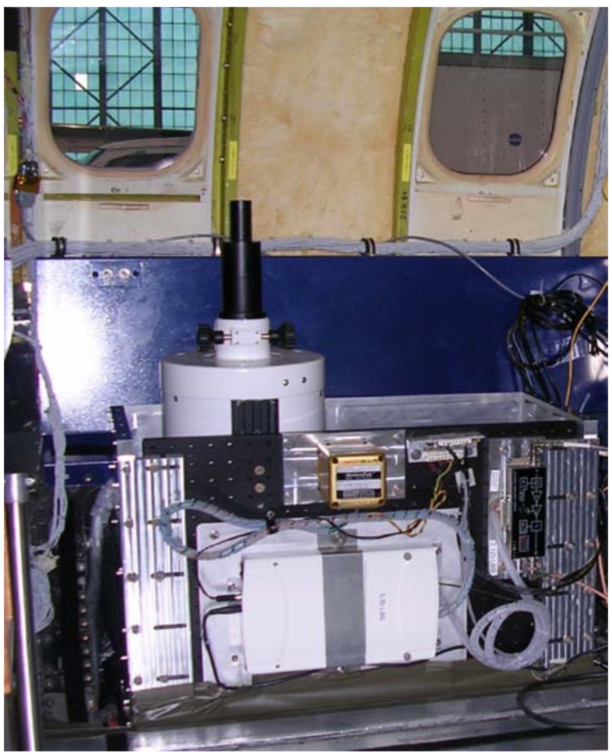
CO_2 & O_2 column measurements:

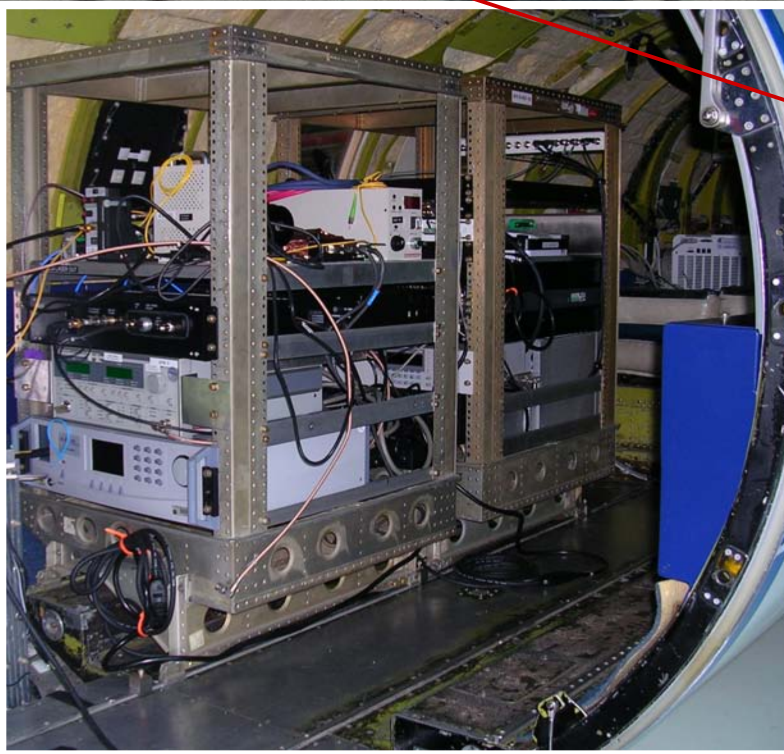
- Pulsed signal approach :
  - Isolate full column signal from surface
  - Reduces noise from detector & solar background
  - Time of flight provides column length

Pulsed Airborne CO2 Sounder Lidar on the NASA Glenn Lear-25

(Airborne demonstration measurements for this approach for ASCENDS)

Experiment Team in Ponca City OK, USA (2008 & 2009)

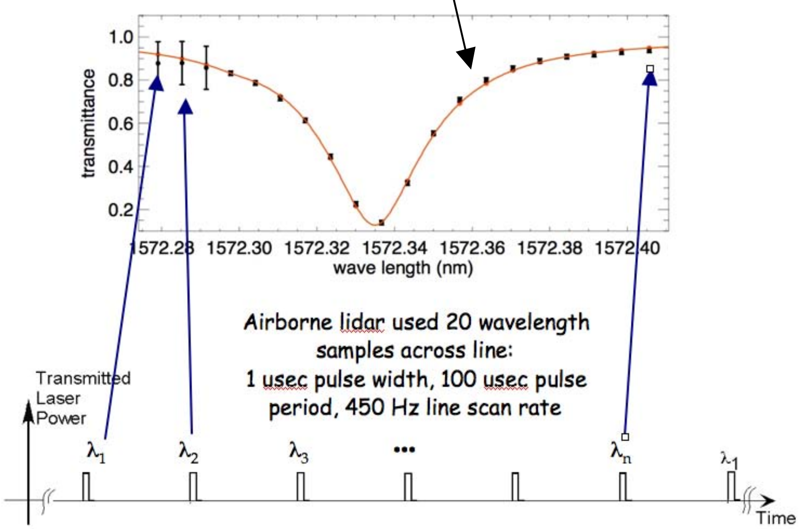




View of nadir port showing transmit and receiver windows

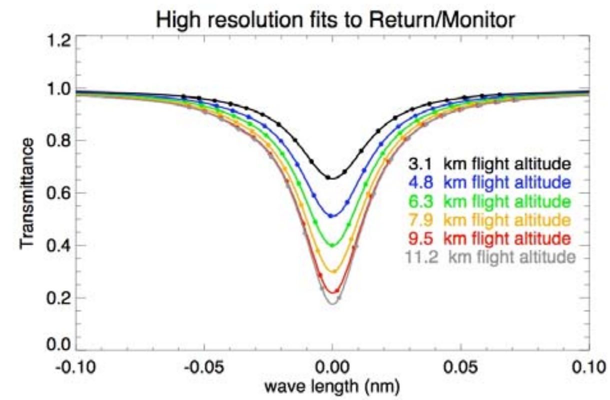
CO2 Band, Airborne Line Sampling & Absorption line analysis

"Dots" - lidar measurements
Fitted absorption line from analysis

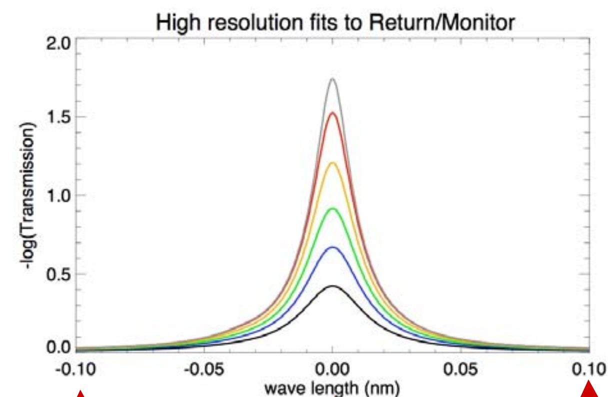


CO2 Line: 1572.33 nm

Line Transmission vs wavelength at increasing alt.'s



Optical Depth of fitted lines at increasing alt.'s



λ_{pk}-100pm λ_{pk} λ_{pk}+100pm

Multi-wavelength Line Sampling allows:

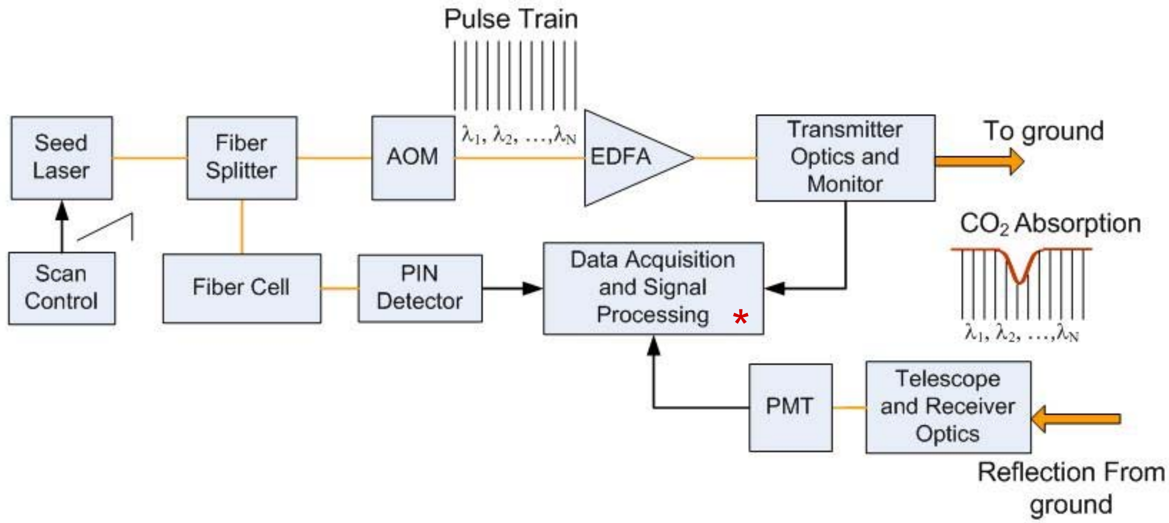
- Detection & correction of Doppler & λ errors
- Modeling & reducing errors from varying λ response
- CO2 retrievals for lower & upper troposphere

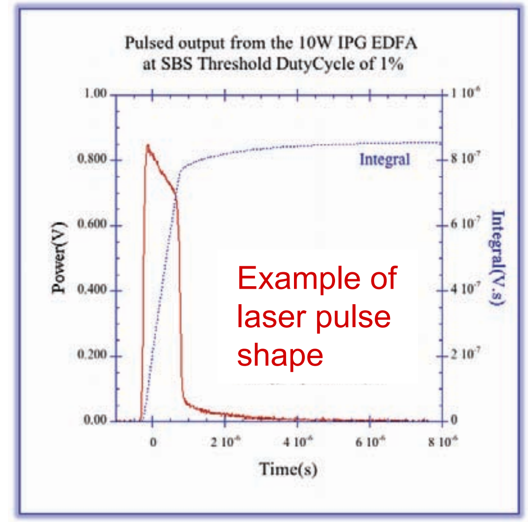
Note: Other λ's may be chosen for analysis

For this analysis:
Retrieved Values:
Line Differential Optical Depth:
DOD =
$$OD(\lambda_{pk}) - [OD(\lambda_{pk}-100) + OD(\lambda_p+100)]/2$$

ESTO Earth Science Technology Office

Pulsed Airborne CO2 Lidar - 2009





2009 CO2 Lidar Parameters:

Laser power & energy:	**0.24 W**, 24 uJ/pulse	Laser divergence angle:	100 urad
Laser pulse width & rate:	1 usec, 10 kHz	Laser type:	DFB diode laser, AOM, Fiber amplifier
CO2 line:	1572.33 nm	Wavelength scans:	20 wavelengths, 450 Hz
Wavelength span:	~114 pm	Wavelength spacing:	6 pm
Telescope diameter:	20 cm	Receiver FOV:	200 urad
Receiver opt. bandwidth:	0.8 nm	Receiver transmission:	65%
Detector quantum efficiency:	~5%	PMT dark count rate:	~ 500 kHz
Receiver range bin size:	8 nsec	Receiver recording duty cycle:	50% (1 sec every 2 sec)

- Configured as space lidar simulator - low laser power (0.24 W)

*- The 2009 receiver’s electronic counter limited maximum recorded signal levels

- Recorded signal rate on 2009 flights was <u>~ x25 weaker</u> (=> noisier) than planned for space

1. Cessna Takeoff
(DOE in-situ CO2 sensor)

2. Twin Otter Takeoff
(JPL 2 um lidar)

3. Lear Takeoff
(GSFC CO2 Sounder lidar)

Coordinated Airborne Experiments to Measure CO2 column densities to support ASCENDS Science Mission Definition

(August 2009)

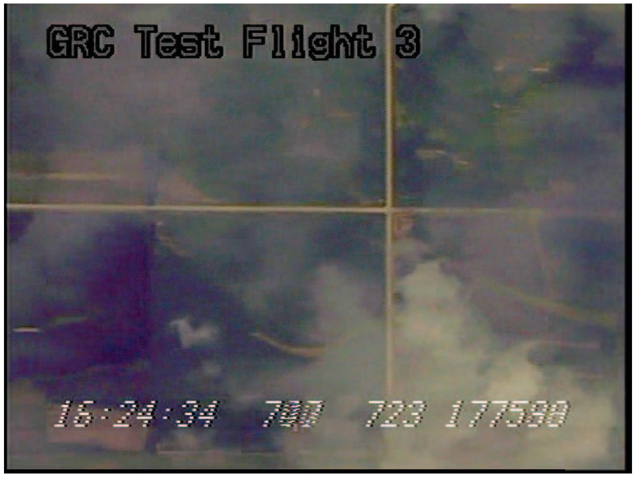
4. UC-12 Takeoff
(LaRC/ITT Lidar, LaRC in-situ)

Checkout on ground
Ponca City Airport, OK

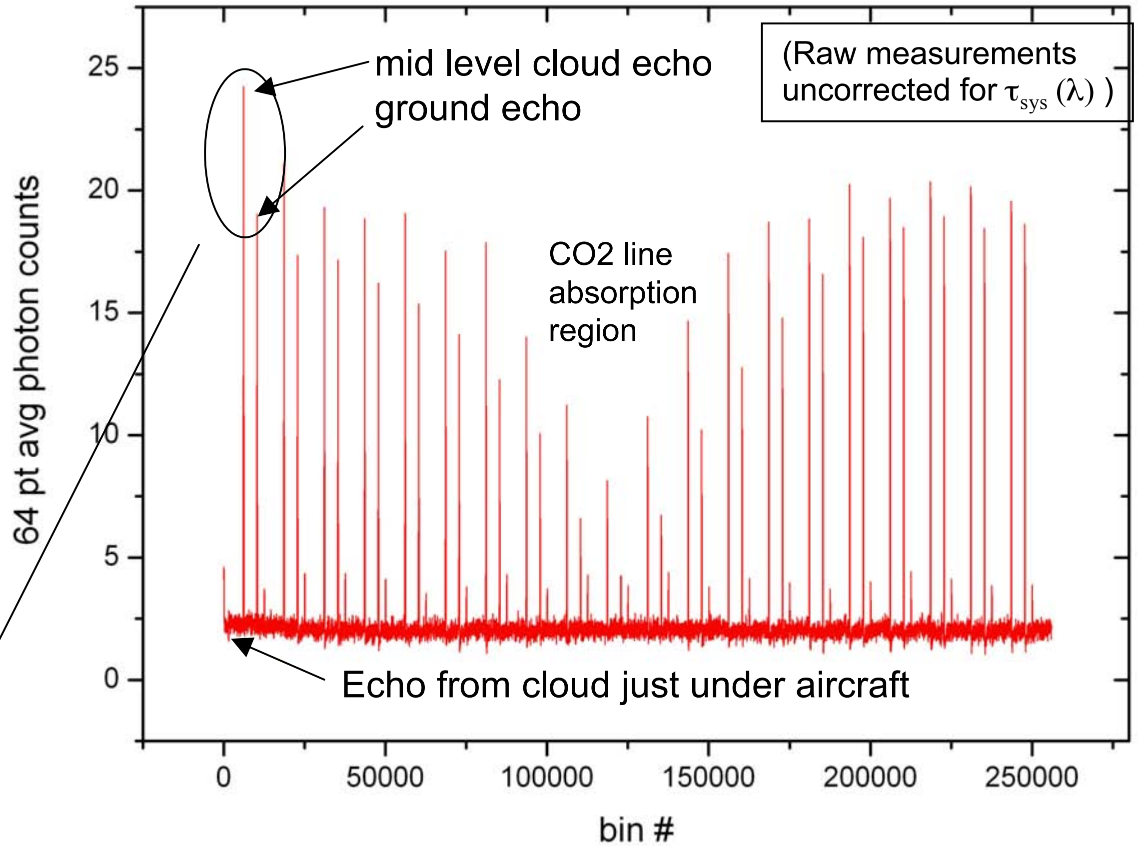
Ed Browell, NASA/LaRC
Experiment Team Leader
(& photos)

Examples of Measurements through 2 Cloud layers (cloud, cloud, ground echo pulses)

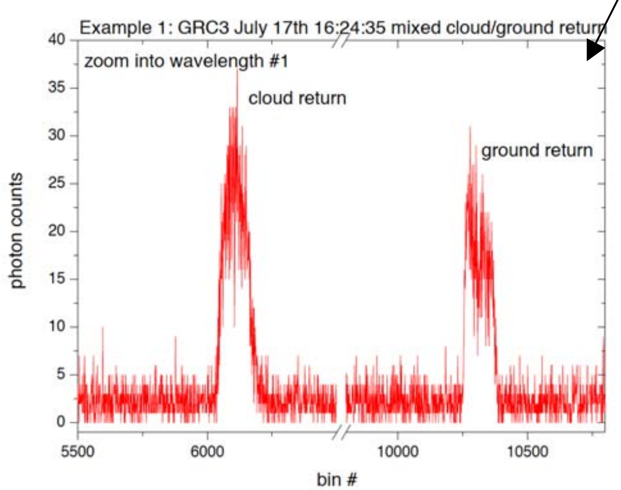
Nadir Camera Image for Measurement



Example 1: GRC3 July 17th 16:24:35 mixed cloud/ground return



Expanded view of 1st echo pulse group in sequence

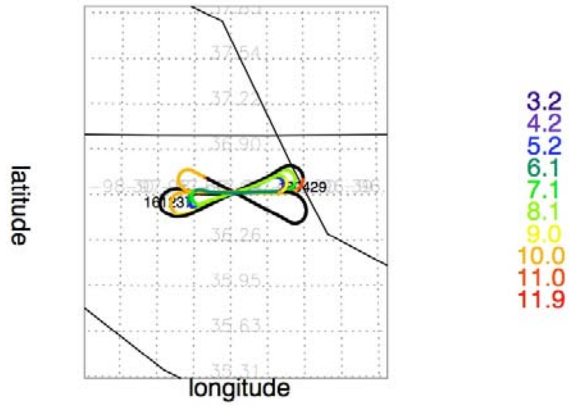


Note:

Absorption line shape to clouds - thinner, less deep

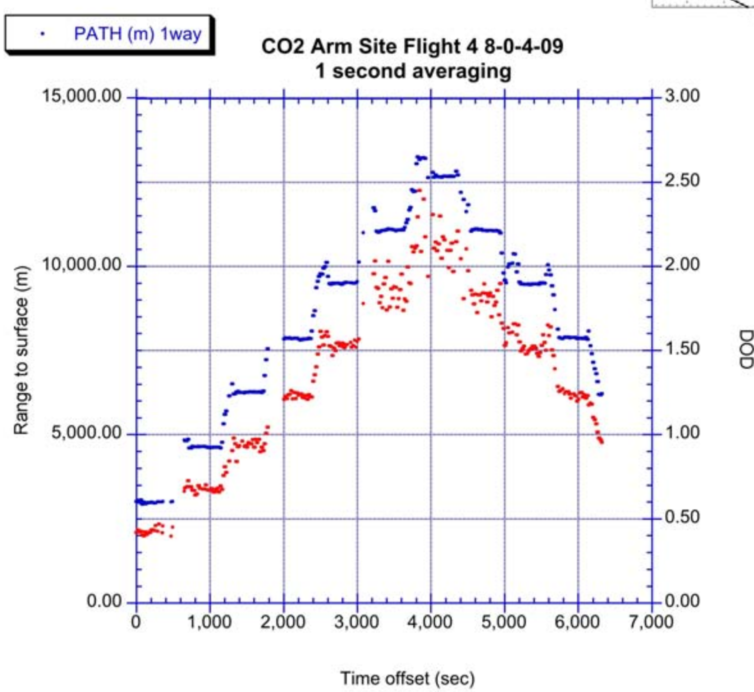
Absorption line shape to ground - broader & deeper

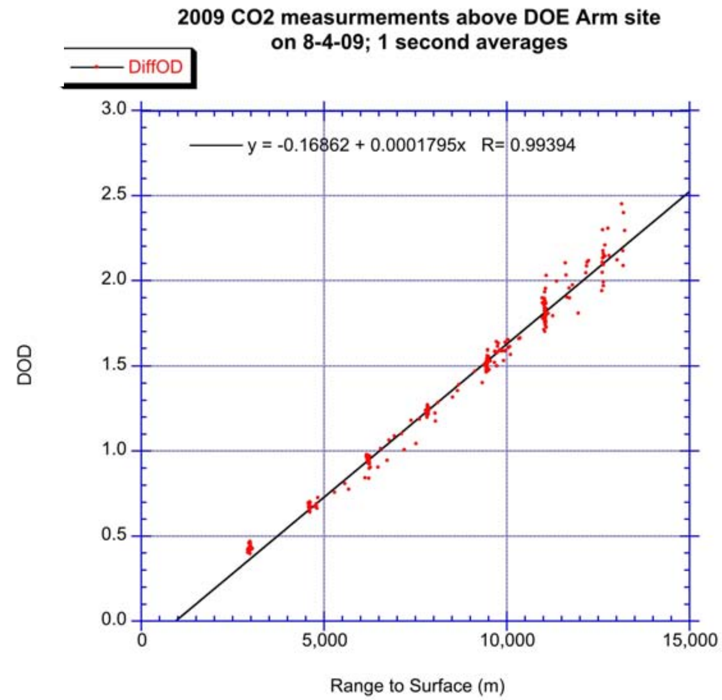
Flight Above DOE Arm Site, Lamont OK on 8-4-09; 1 second averages (Uncalibrated)



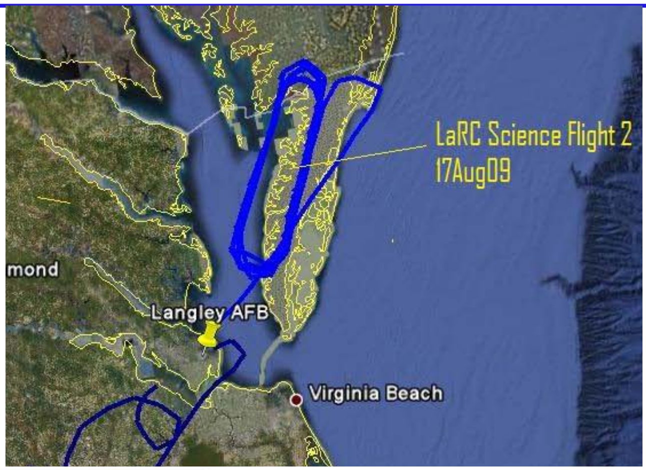
1747 measurements
Min {σ (range)}= 3 m

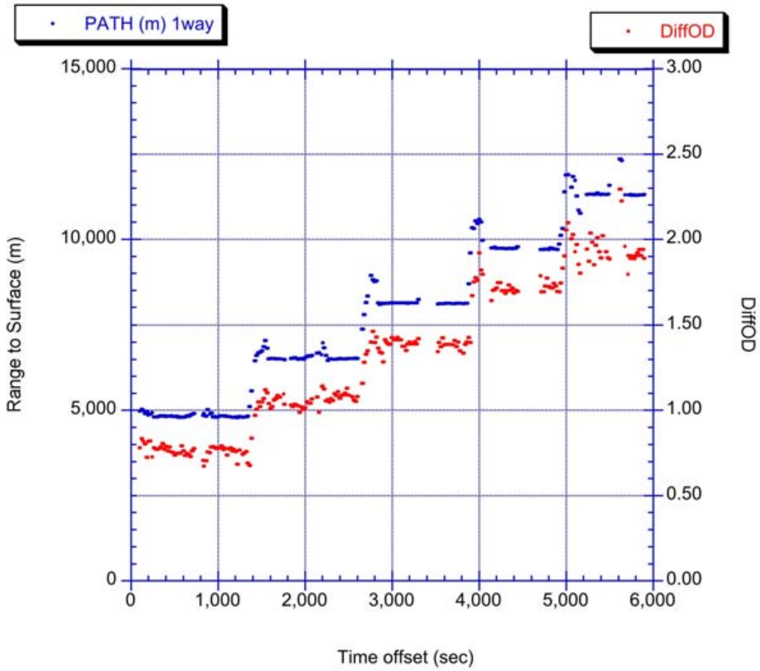
Measured DOD vs range is quite linear





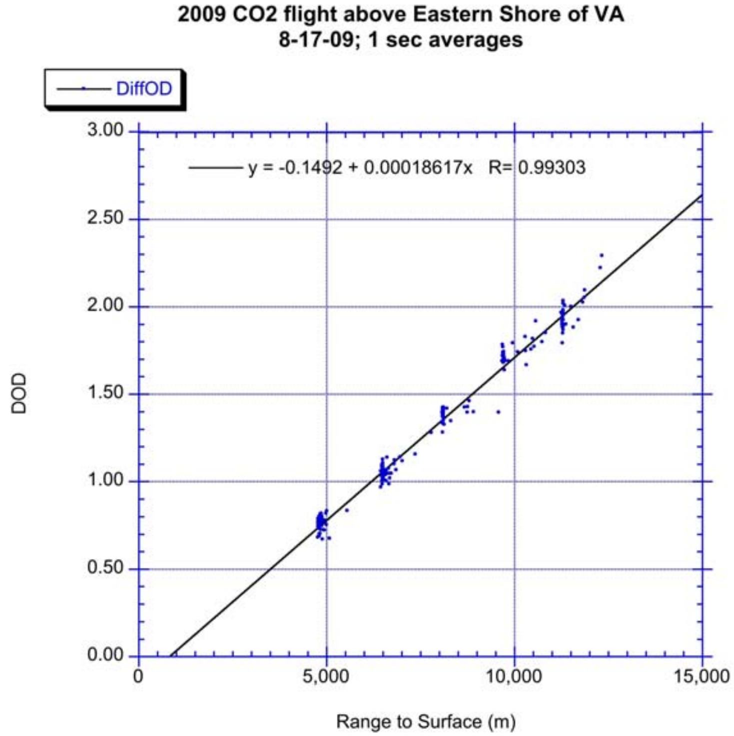
Flight Above Eastern Shore of VA on 8-17-09
1 second averages, Uncalibrated





2031 measurements
Min {σ (range)}= 1.8 m

Measured DOD vs range is quite linear



2009 - Ave'd column DOD Measurement (uncalibrated) with in-situ & HITRAN 08

DOD fits from in-situ & HITRAN 08

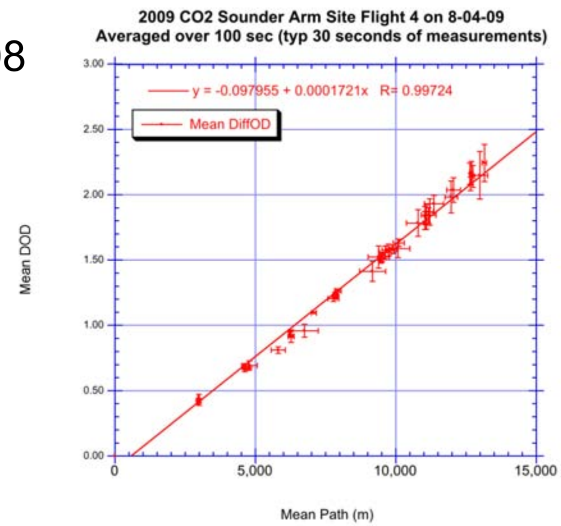
2009 Flight comparisons of DOD

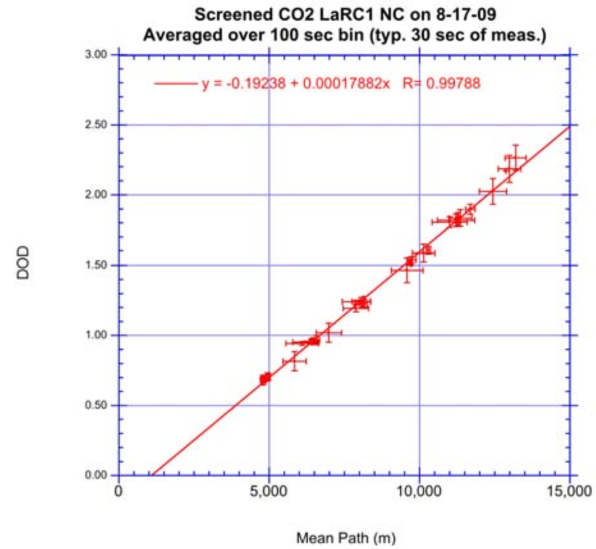
Location	Hitran DOD Slope*	Averaged Airborne Lidar Slope*
ARM Site	160	172
Homer IL	160	163
NC	156	179
VA	160	178
Averages:	159	173

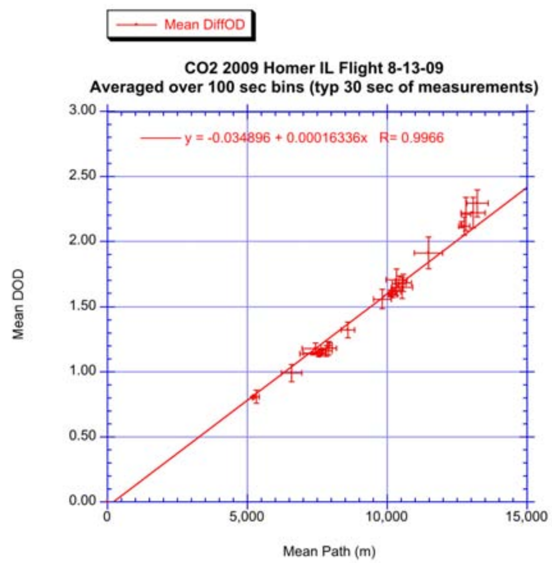
*: * 1.e-6/m

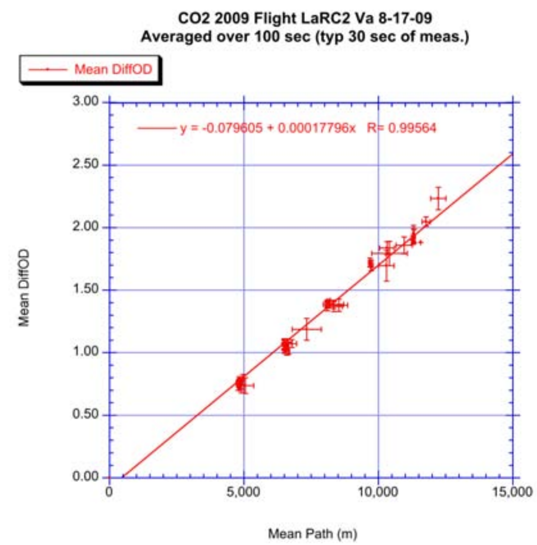
Percent Difference: (Airborne/Hitran)	8.8

Using in-situ measurements for calibration removes slope and offset differences

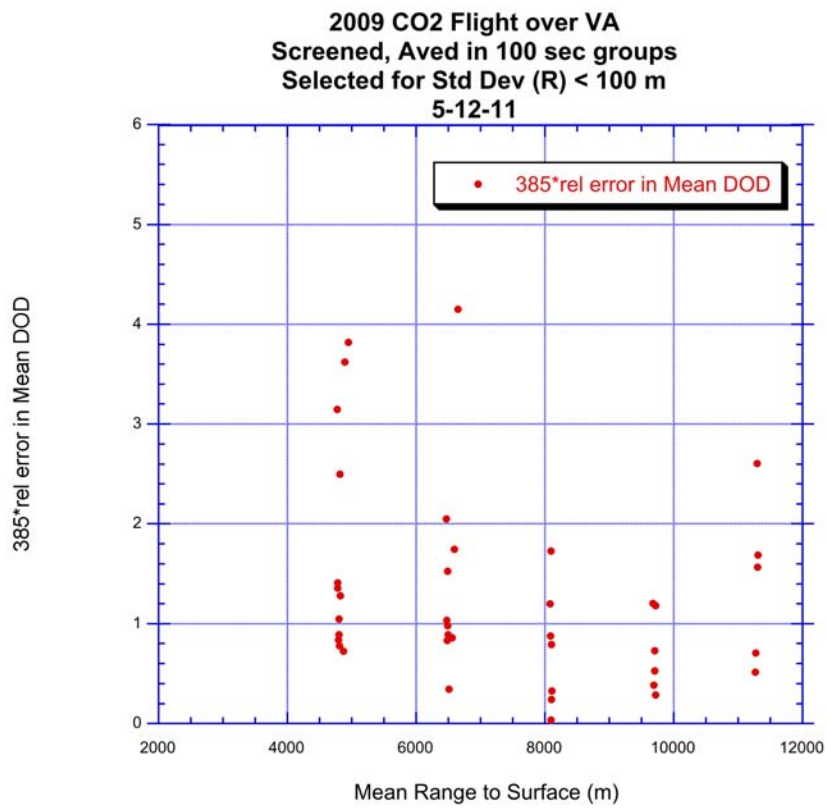


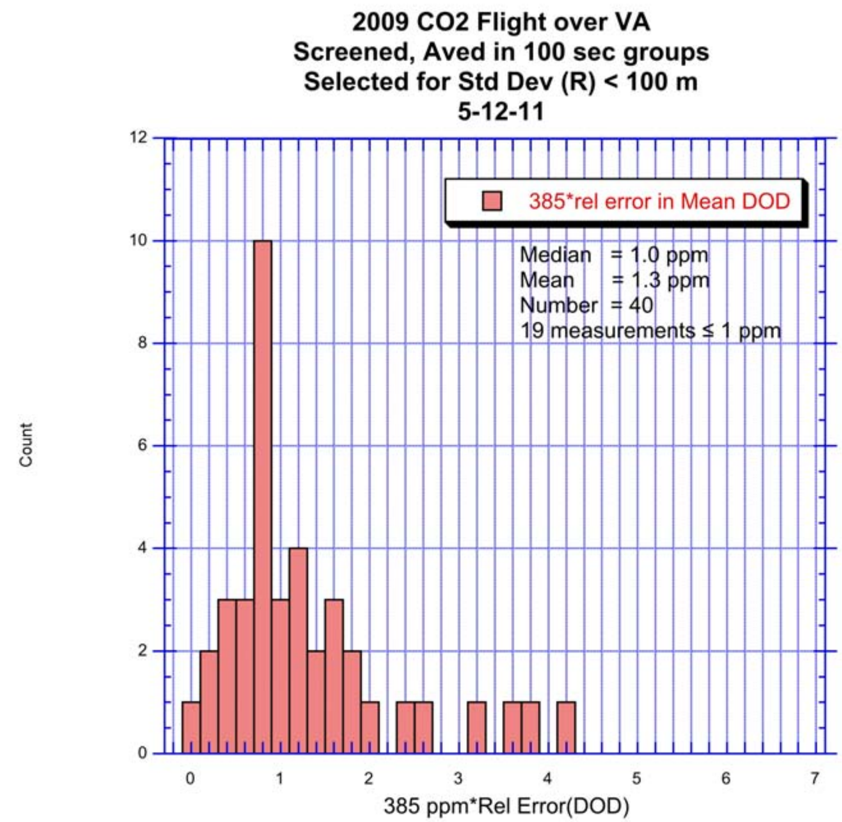






2009 measurements - VA Flight
Constant altitude segments





Median error = 1.0 ppm
For R = [8-10 km] errors ~0.5 ppm

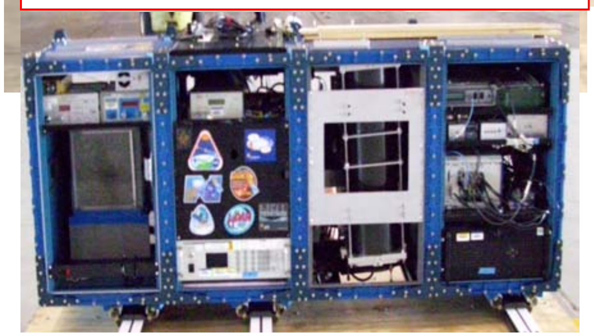
Airborne Experiments to Measure CO_2 Column Densities to Support ASCENDS Mission Definition; July 5-18, 2010

Objective: Measure & compare CO_2 column densities over various topographic targets with developmental lidar candidates for the ASCENDS mission

5 science flights over different regions & topography

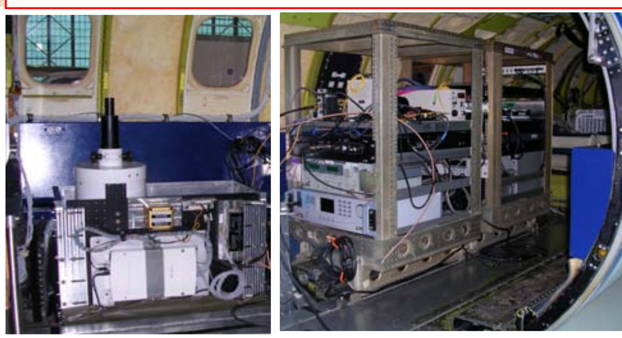
Altitudes: 3-13 km (in ~3 km steps),+ spiral to near surface

LaRC/ITT instrument



- Multi-functional Fiber Laser Lidar (MFLL)
- Ed Browell/LaRC, Team Leader
- Instrument development via ITT IRAD, NASA AITT funding, LaRC IRAD

GSFC instrument

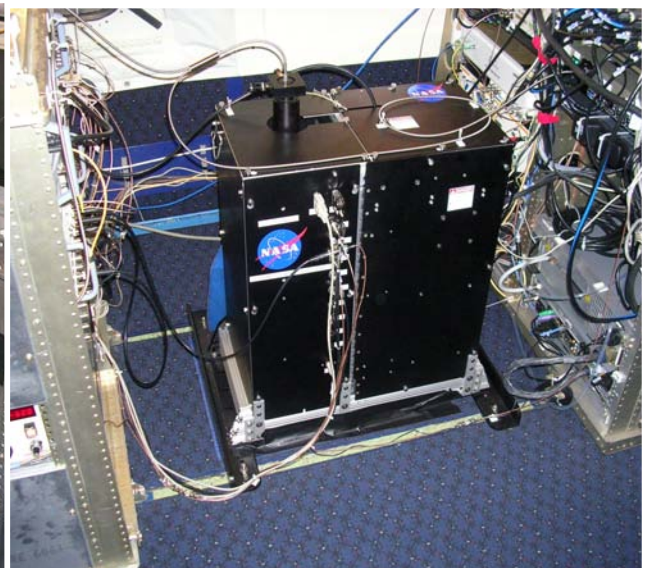


- CO_2 Sounder lidar with O_2 measurement experiment
- Jim Abshire/GSFC, Team Leader
- Instrument development via NASA ACT & IIP programs, GSFC IRAD

JPL/LMCT instrument

- CO_2 laser absorption spectrometer (CO_2LAS)
- Gary Spiers/JPL, Team Leader
- Instrument development via NASA ACT, IIP & AITT programs, JPL IRAD

July 2010 CO_2 Sounder Configuration flown on NASA DC-8



2010 CO_2 lidar improvements:

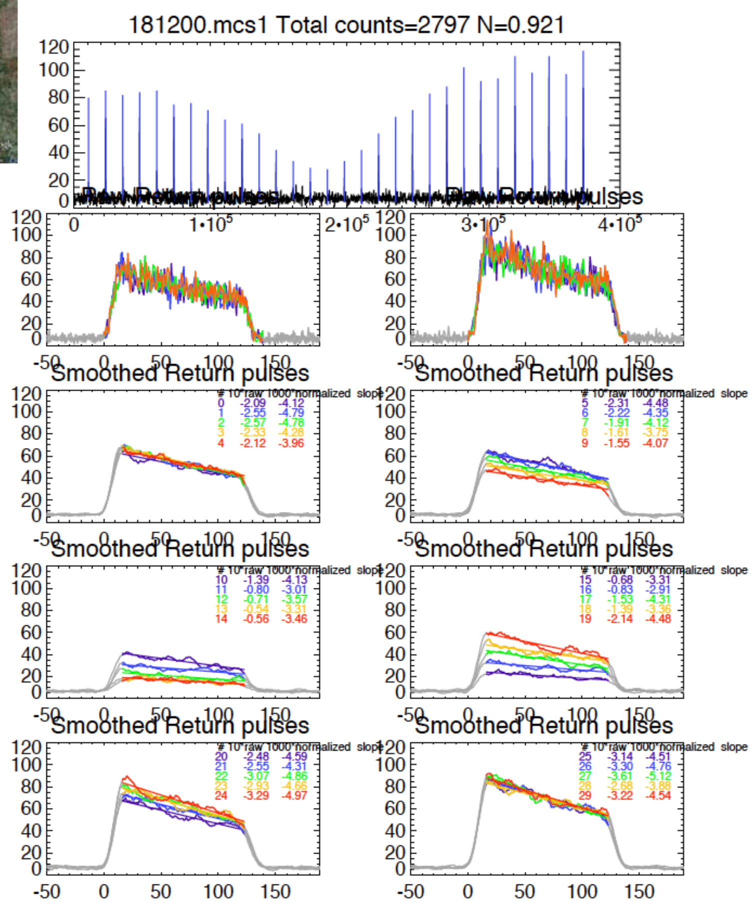
- Improved receiver photon counter
  - -> ~x3 stronger recorded signals
- Increased λ samples across line ~x2
- Increased recording duty cycle x4/3
- Consistent settings during operation
- Added O_2 lidar experiment
- Better temperature control on DC-8

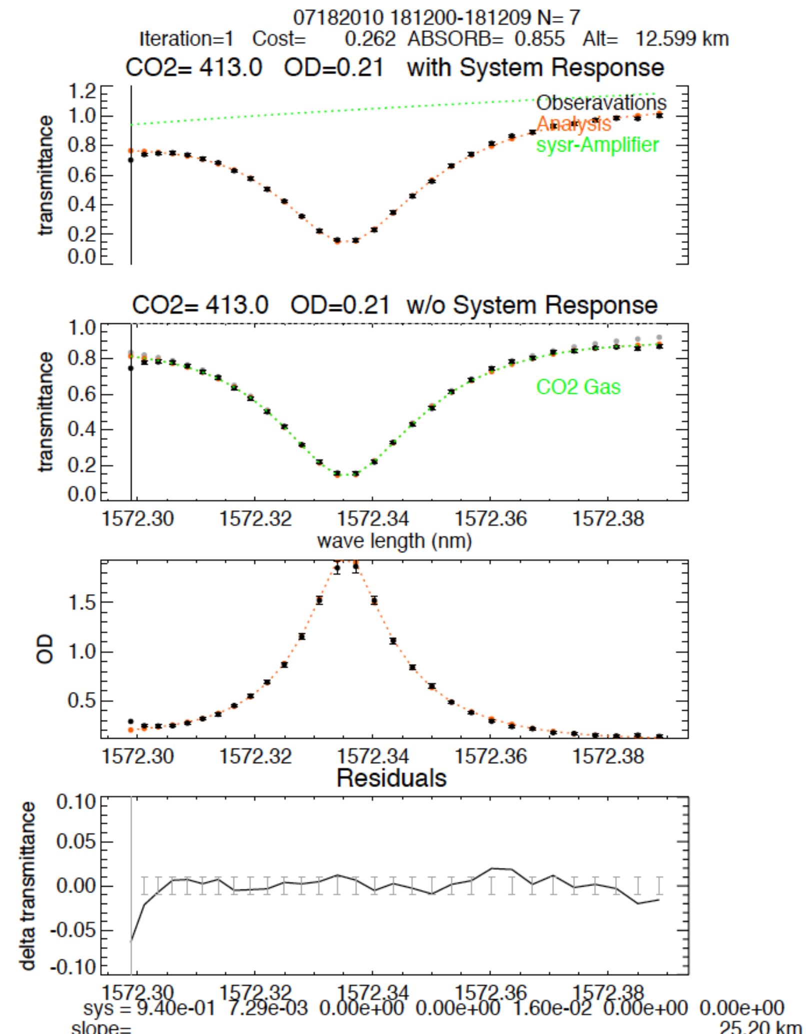
CO_2 Results:

- Recorded signal increased ~x9
- Better constrained line fits

2010 Echo Pulse and CO2 Line Shape Examples
DOE ARM Site Flight 7-18-10

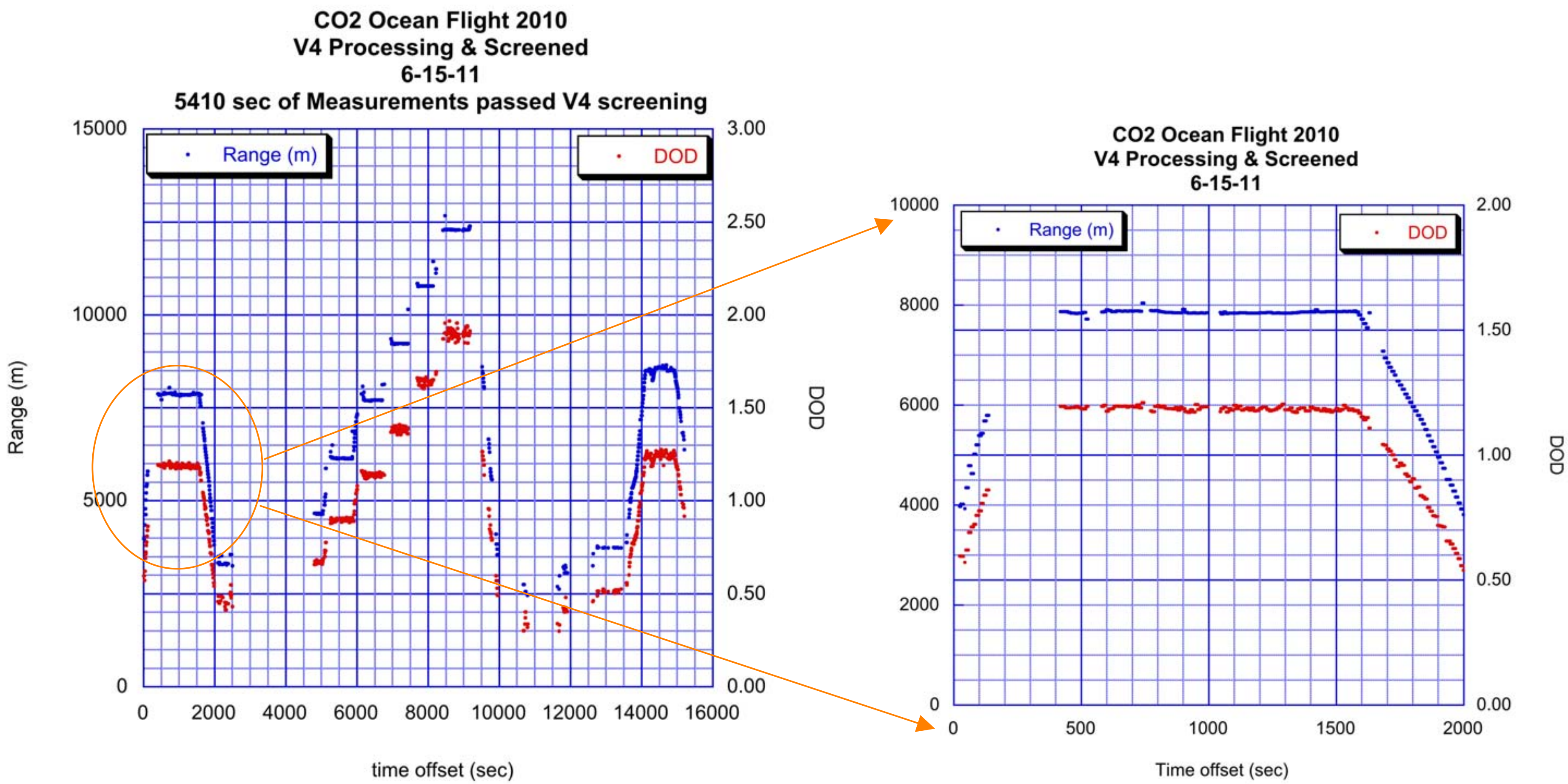
CO_2 Lidar Settings for last 3 2010 flights:
- 30 samples across line
- Wavelength span = 87 pm
- Wavelength spacing = 3 pm



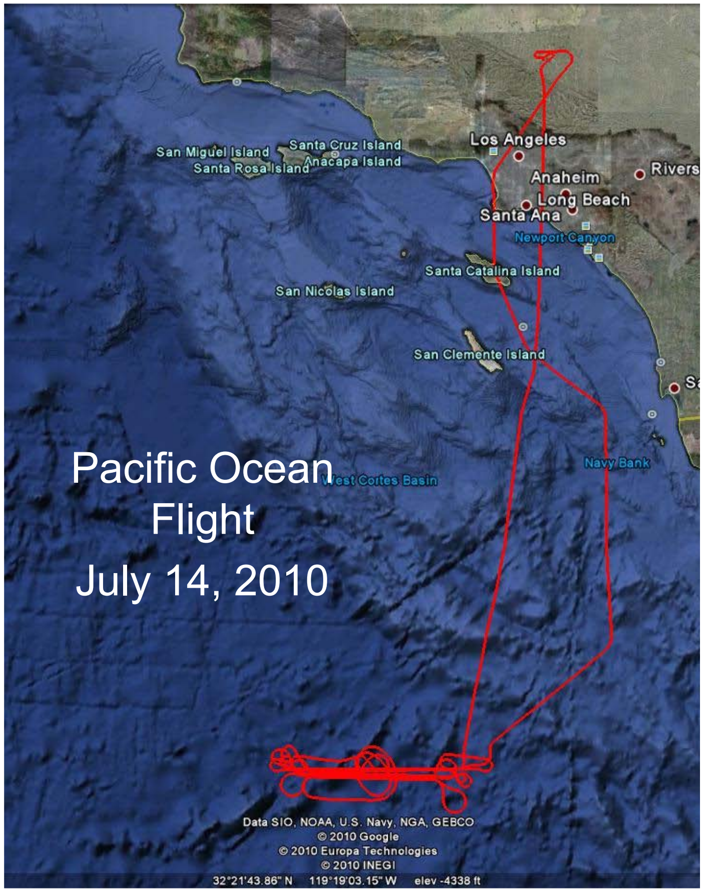


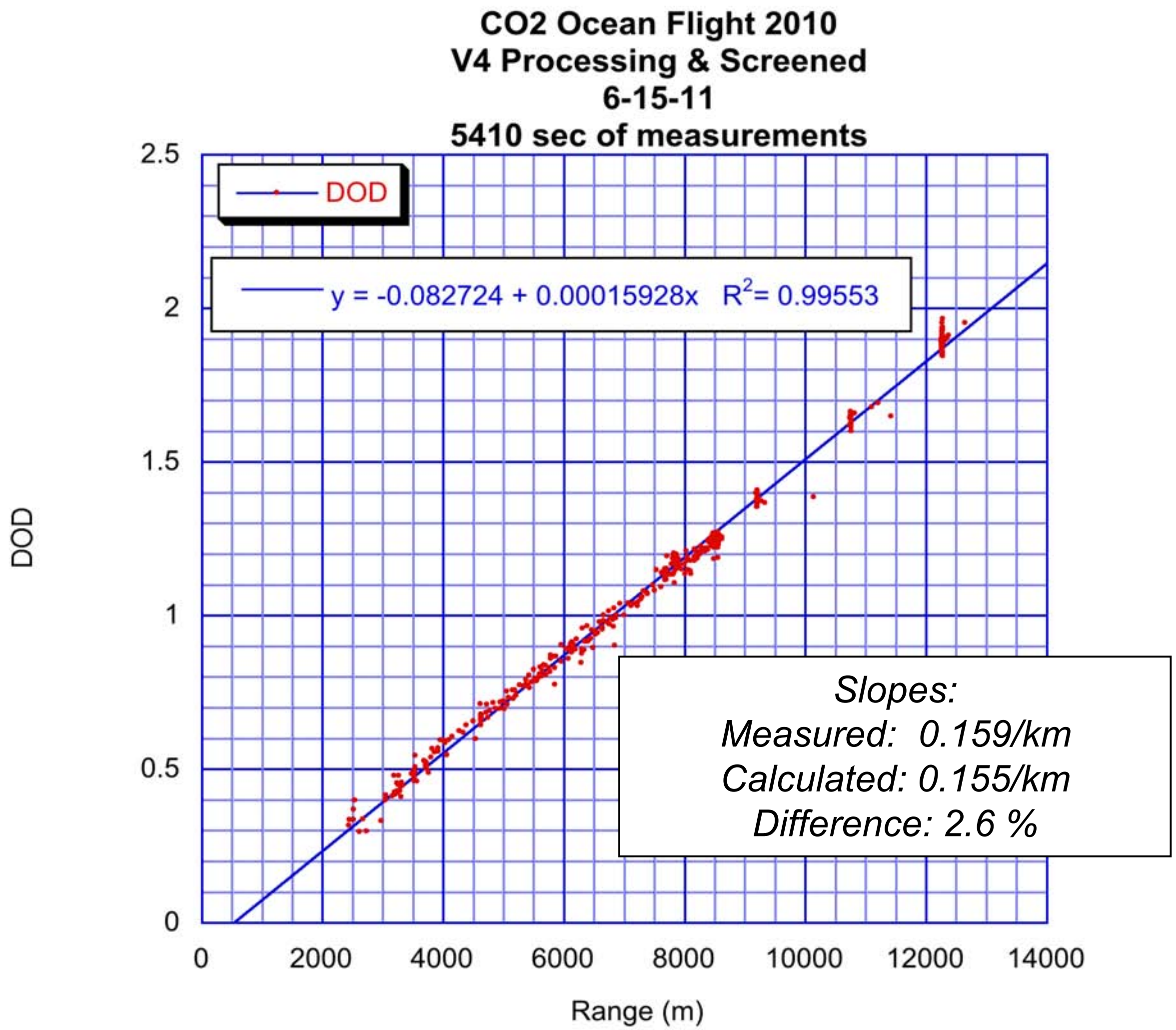
Very good line fits (low fit errors)

2010 Airborne CO2 Measurements
Pacific Ocean Flight, July 14, 2010



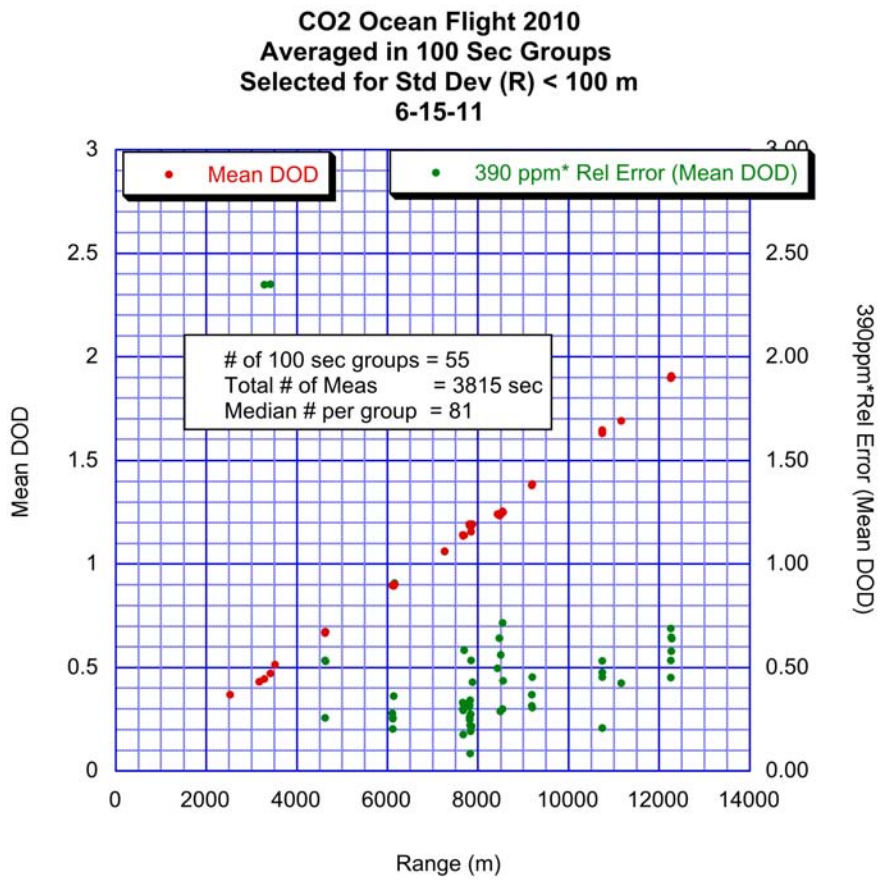
2010 Airborne CO2 Measurements Pacific Ocean Flight, July 14, 2010

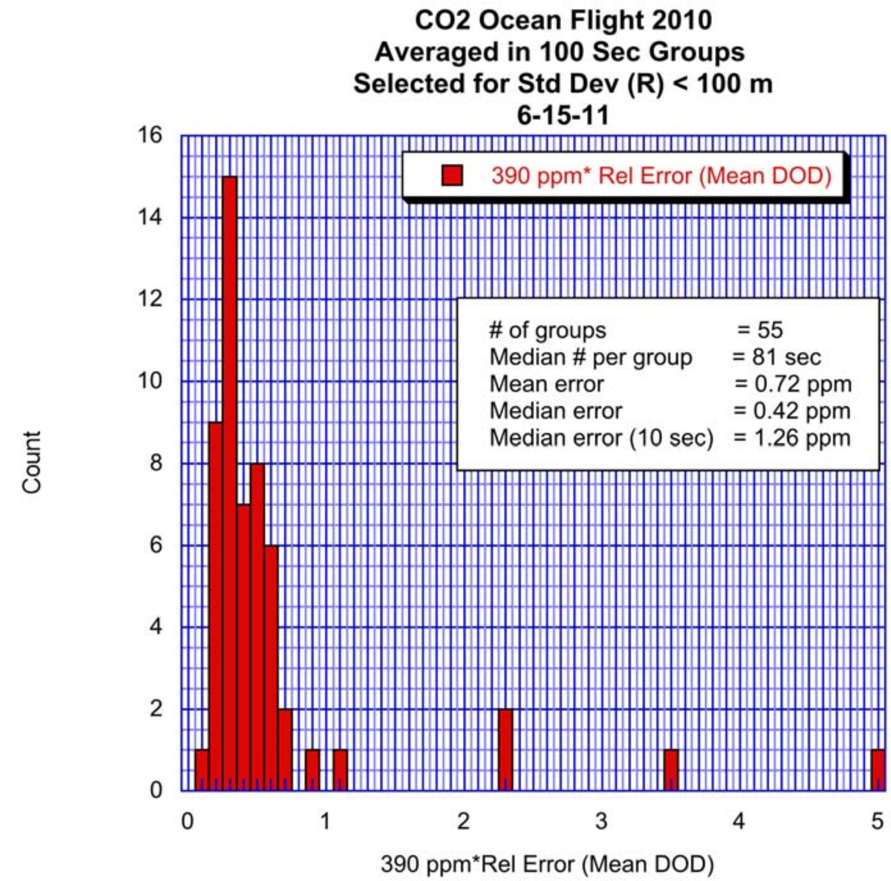




2010 Airborne CO2 Measurements
Pacific Ocean Flight, July 14, 2010

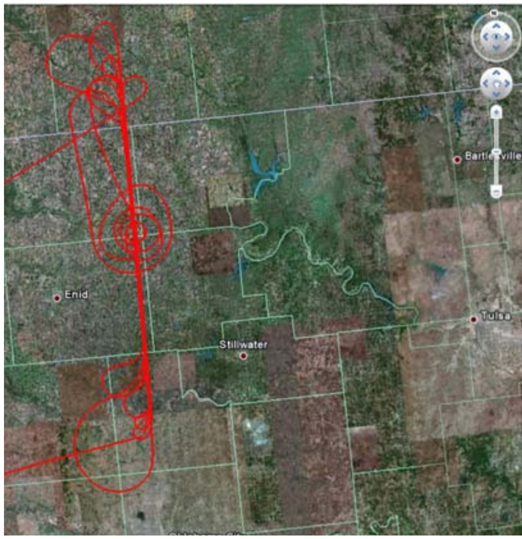
Median random error (80 sec ave) = 0.42 ppm





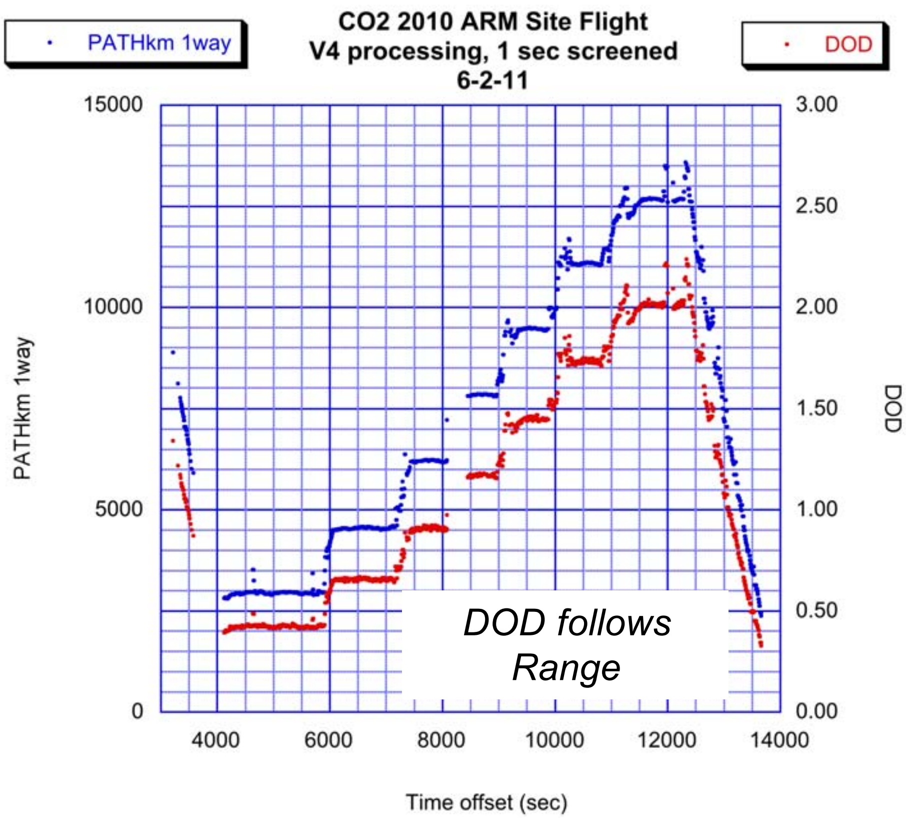
NASA Goddard

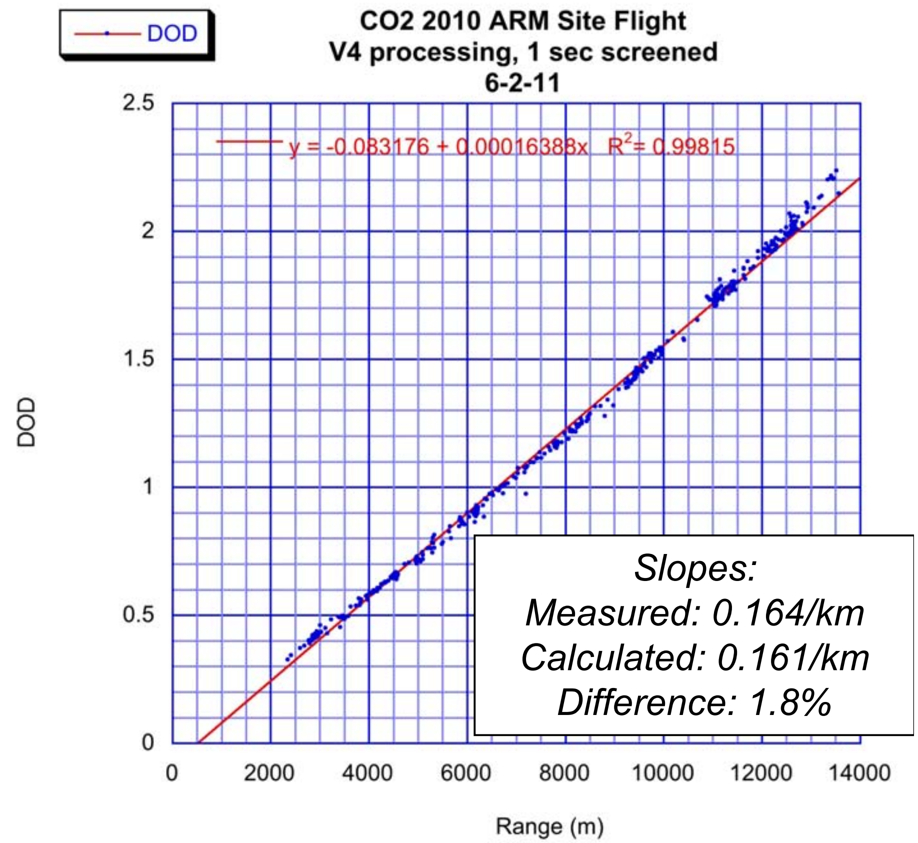
CO2 2010 Flight Measurements
DOE SGP ARM Site Flight 7-18-10



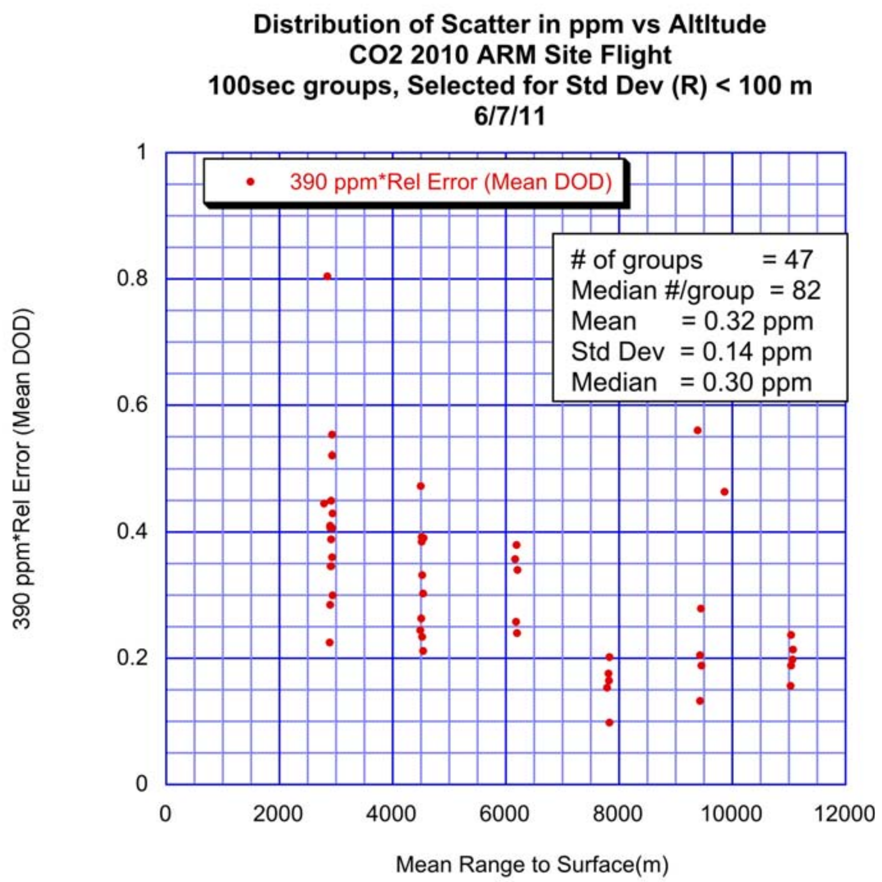
~ 6900 accepted measurements/flight

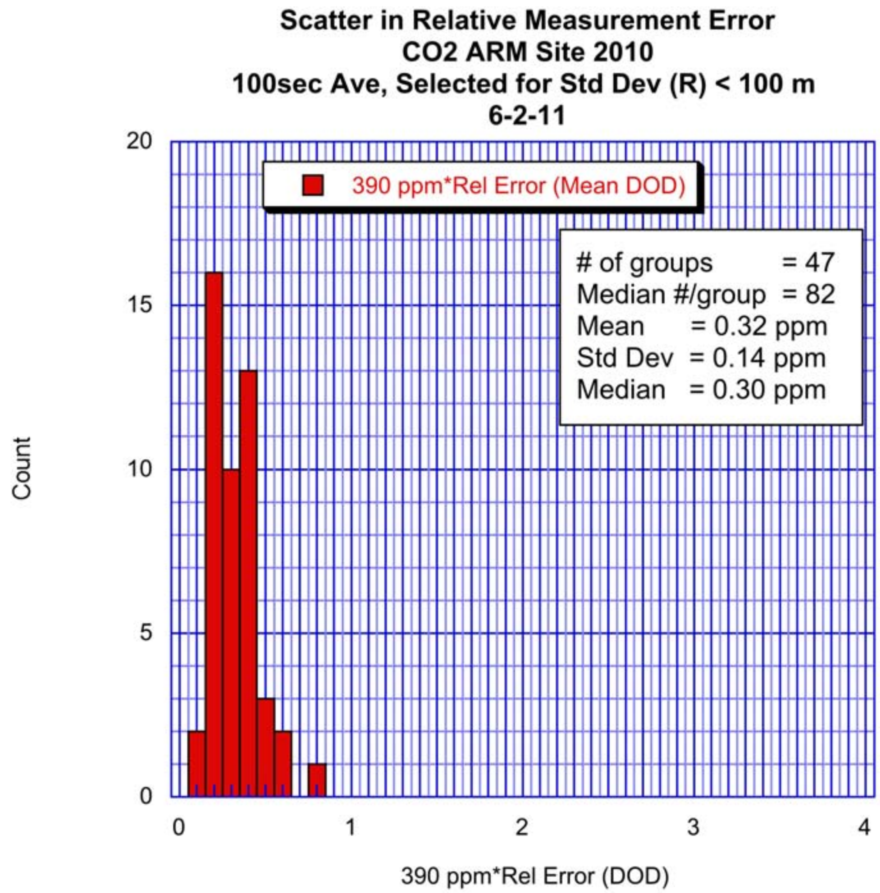
Very smooth ~ linear change of DOD with Range





2010 CO2 Flight Measurements
Arm Site Flight on 7-18-10



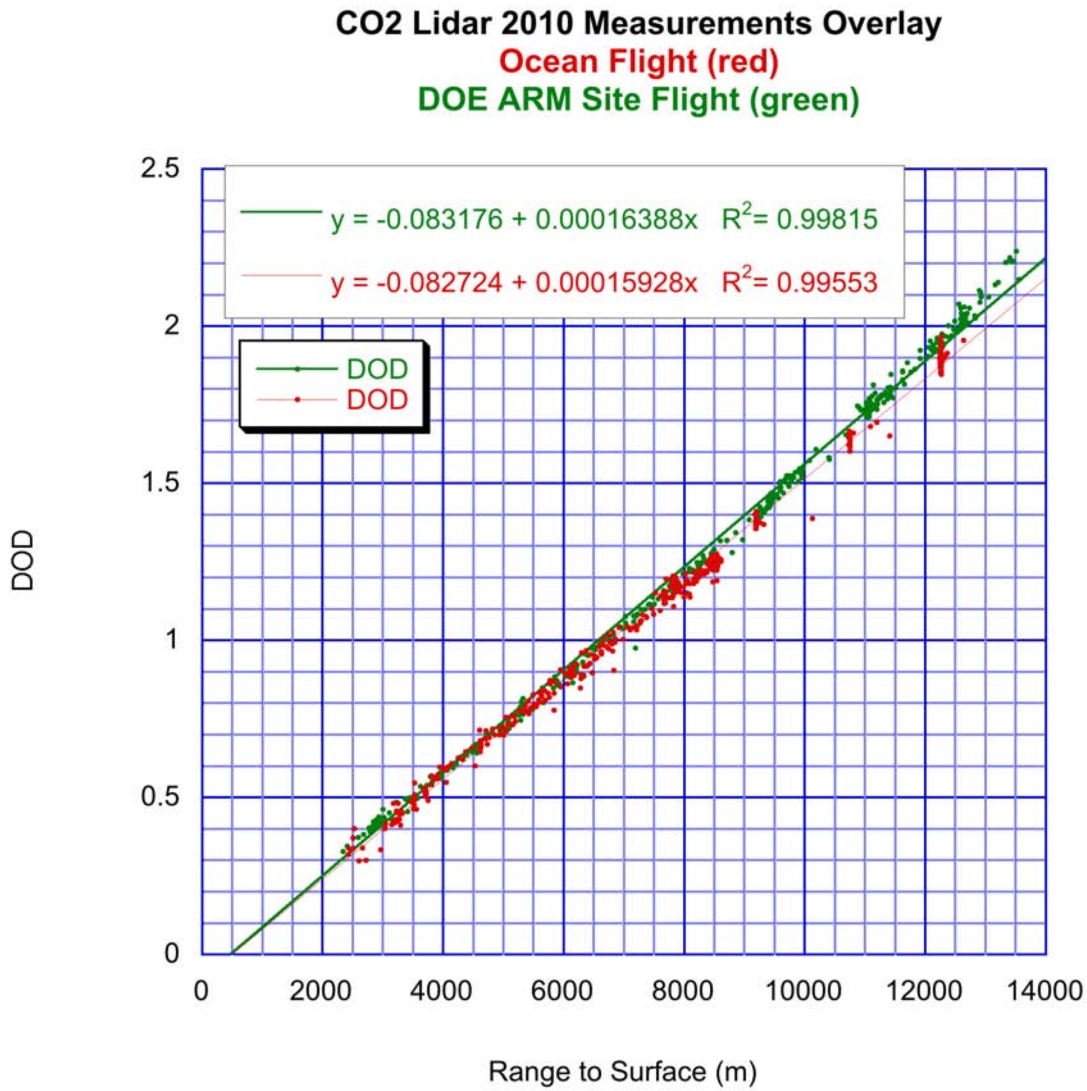


- Median random error (80 sec ave): 0.30 ppm
- Min error (~ 8km, 80 sec ave): <0.2 ppm

=> Median error (10 sec ave): 0.9 ppm
- Similar performance: 8-12 km

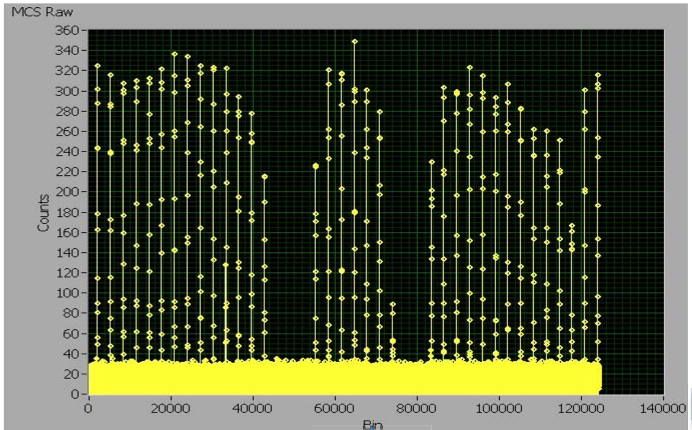
2010 Measurement Comparison
Ocean & ARM Site Flights

- In-situ measurements & calculations show higher CO2 column density above ARM site
- Measured DOD slopes:
  ARM Site > Ocean flight
- Lidar readings are consistent with predictions
- Lidar measurements made:
  - 4 days apart
  - Over different surfaces
- Quite encouraging !

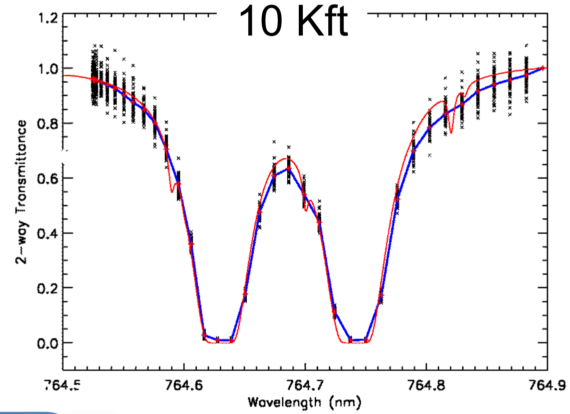


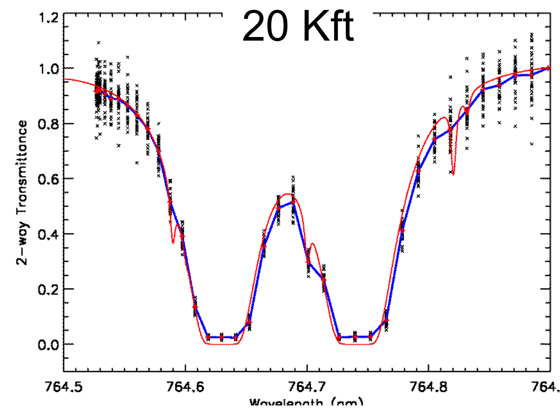
Airborne O2 Column Measurements ~765 nm on 2010 Ocean Flight (Haris Riris)

Observations (Lidar echos)



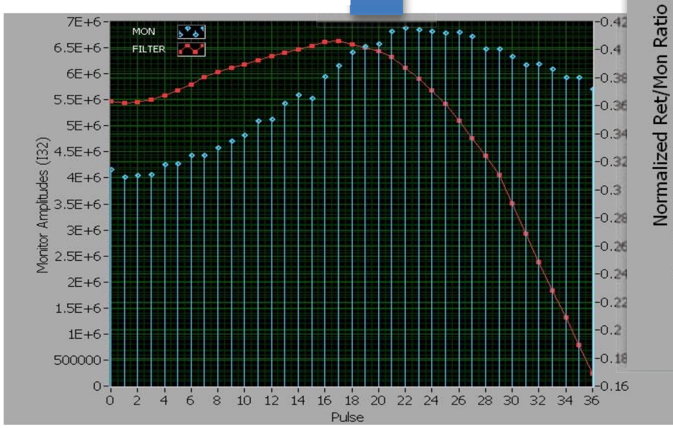
Results:

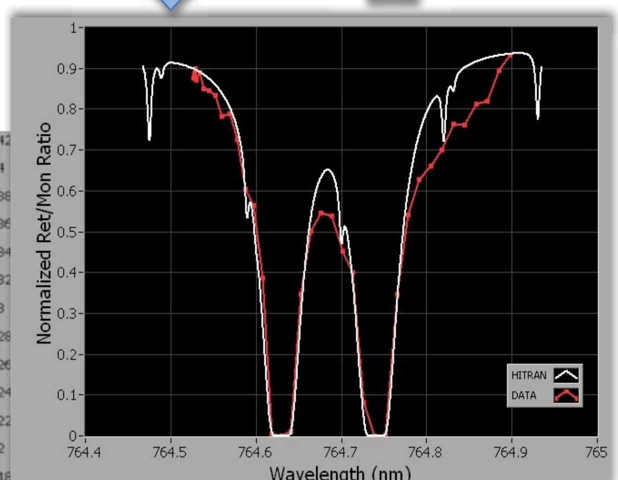


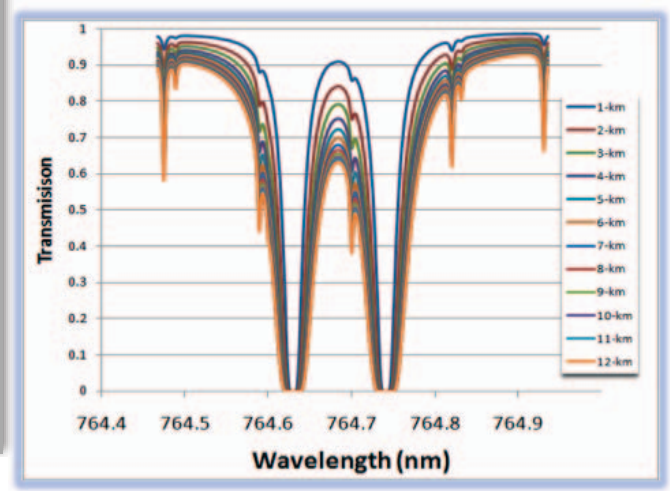


1 sec Average
10 min Average
HITRAN Prediction

Normalizations







Predicted from Altimetry, T, P, HITRAN

Summary

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission

NASA Science Definition and Planning Workshop Report

July 23-25, 2008
University of Michigan in Ann Arbor, Michigan

Workshop report:
http://cce.nasa.gov/ascends/index.htm

Made significant progress in developing the CO2 Sounder approach & key technologies:

- CO2 and O2 (pressure) measurements
  - Line shape & column height measurements
  - Robust against atmospheric scattering
- 1st mission simulations show can meet science needs
- Airborne demonstrations for ASCENDS definition:
  - 2009: CO2 measurements - analyzed, 1 ppm error
  - 2010: CO2 measurements show 0.3 ppm errors
    - O2 absorption measurements demonstrated
- 2011: flights in July: more CO2 & O2 improvements
- New IIP-10 award concentrates on “scaling to space”:
  - Laser amplifiers (4 mJ energy): Raytheon
  - More sensitive long life CO2 detector: DRS

We appreciate the ESTO support !

More Information

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Pulsed airborne lidar measurements of atmospheric CO_2 column absorption

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(Manuscript received 29 December 2009; in final form 22 July2010)

ABSTRACT

We report initial measurements of atmospheric CO_2 column density using a pulsed airborne lidar operating at 1572 nm. It uses a lidar measurement technique being developed at NASA Goddard Space Flight Center as a candidate for the CO_2 measurement in the Active Sensing of CO_2 Emissions over Nights, Days and Seasons (ASCENDS) space mission. The pulsed multiple-wavelength lidar approach offers several new capabilities with respect to passive spectrometer and other lidar techniques for high-precision CO_2 column density measurements. We developed an airborne lidar using a fibre laser transmitter and photon counting detector, and conducted initial measurements of the CO_2 column absorption during flights over Oklahoma in December 2008. The results show clear CO_2 line shape and absorption signals. These follow the expected changes with aircraft altitude from 1.5 to 7.1 km, and are in good agreement with column number density estimates calculated from nearly coincident airborne in-situ measurements.

Approach & 2008 flights

1. Introduction

Atmospheric CO_2 is presently understood as the largest anthropogenic forcing function for climate change, but there is considerable uncertainty about the global CO_2 budget. Accurate measurements of tropospheric CO_2 abundances are needed to study CO_2 exchange with the land and oceans. To be useful in reducing uncertainties about carbon sources and sinks the atmospheric CO_2 measurements need to have high resolution, with ~ 0.3% precision (Tans et al., 1990; Fan et al., 1998). The GOSAT mission (Yokota et al., 2004) is making new global CO_2 measurements from space using a passive spectrometer and surface reflected sunlight. However sun angle limitations restrict its measurements to the daytime primarily over mid-latitudes. A concern for measurement accuracy with passive instruments is optical scattering from thin clouds in the measurement path (Mao and Kawa, 2004; Aben et al., 2007). Optical scattering in the measurement path modifies the optical path length and thus the total CO_2 absorption viewed by the instrument. For measurements using spectrometers with reflected sunlight optical scattering can cause large retrieval errors even for thin cirrus clouds (Uchino et al., 2009).

To address these issues, the US National Research Council's 2007 Decadal Survey for Earth Science recommended a new space-based CO_2 measuring mission called Active Sensing of CO_2 over Nights, Days, and Seasons, or ASCENDS (US NRC, 2007). The goals of the ASCENDS mission are to produce global atmospheric CO_2 measurements with much smaller seasonal, latitudinal, and diurnal biases by using the laser absorption spectroscopy measurement approach. The mission's goals are to quantify global spatial distribution of atmospheric CO_2 with 1–2 ppm accuracy, and quantify the global spatial distribution of terrestrial and oceanic sources and sinks of CO_2 on 1-degree grids with 2–3 week time resolution. The ASCENDS approach offers continuous measurements over the cloud-free oceans, at low sun angles and in darkness, which are major improvements over passive sensors. ASCENDS mission organizers held a workshop in 2008 to better define the science and measurement needs and planning for future work (NASA, 2008). ESA has also conducted mission definition studies for a similar space mission called A-SCOPE (ESA, 2008; Durand et al., 2009). Although the ASCENDS mission concept requires

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A Lidar Approach to Measure CO_2 Concentrations from Space for the ASCENDS Mission

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ABSTRACT

We report on a lidar approach to measure atmospheric CO_2 column concentration being developed as a candidate for NASA's ASCENDS mission. It uses a pulsed dual-wavelength lidar measurement based on the integrated path differential absorption (IPDA) technique. We demonstrated the approach using the CO_2 measurement from aircraft in July and August 2009 over various locations. The results show clear CO_2 line shape and absorption signals, which follow the expected changes with aircraft altitude from 3 to 13 km. The column absorption measurements show altitude dependence in good agreement with column number density estimates calculated from airborne in-situ measurements. The approaches for O_2 measurements and for scaling the technique to space are discussed.

Laser Diode locking to CO2 line

Frequency stabilization of distributed-feedback laser diodes at 1572 nm for lidar measurements of atmospheric carbon dioxide

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We demonstrate a wavelength-locked laser source that rapidly steps through six wavelengths distributed across a 1572.335 nm carbon dioxide (CO_2) absorption line to allow precise measurements of atmospheric CO_2 absorption. A distributed-feedback laser diode (DFB-LD) was frequency-locked to the CO_2 line center by using a frequency modulation technique, limiting its peak-to-peak frequency drift to 0.3 MHz at 0.8 s averaging time over 72 hours. Four online DFB-LDs were then offset locked to this laser using phase-locked loops, retaining virtually the same absolute frequency stability. These online and two offline DFB-LDs were subsequently amplitude switched and combined. This produced a precise wavelength-stepped laser pulse train, to be amplified for CO_2 measurements.

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